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FAR INFRARED MERCURY-CADMIUM-TELLURIDE PHOTOCONDUCTIVE DETECTOR--ETC(U)
SEP 80 C J SUMMERS, J G BROERMAN F49620-78-C-0072

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurements of the excess-electron lifetime, electron concentration, electron mobility, and photoconductive spectral response were performed on HgCdTe alloys with 17 to 24% CdTe between 5 K and 300 K. The temperature dependence of the electron concentration was well fitted by the Kane band model using energy gap determinations from photoconductivity measurements and assuming donor levels with ionization energies between 0 and 7 meV. The level of sample compensation was determined from fits to the electron mobility, which was limited by impurity scattering below 80 K. The temperature dependence of the excess-

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electron lifetime was analyzed with a photoconductivity theory which includes intrinsic and defect recombination mechanisms and effects from the surface recombination velocity and incident background photon flux. For all sample compositions, a characteristic dependence of electron lifetime on temperature was observed. Above 100 K the lifetime decreases with temperature and is limited by intrinsic Auger recombination. Below 100 K the lifetime decreases with decreasing temperature because of Shockley-Read recombination. A large increase in the lifetime below 40 K is observed and attributed to minority carrier trapping.

Magneto-photoconductivity measurements were performed from 5 to 300 K for magnetic-field strengths of 0-9 T. Good agreement was obtained between measured interband magneto-optical transition energies and theoretical band structure calculations. At 5 K the excess-electron lifetime increased by one to two orders of magnitude for magnetic-field strengths up to 9 T. A theory of the Auger recombination rate in a magnetic field was formulated and shown to be in good agreement with experiment at high field strengths. The lifetime increases with magnetic field because of spin depopulation effects at low fields and a decrease in the density of final states for the Auger transition at high magnetic-field strengths.

Calculations were made of detector performance as a function of alloy composition, temperature, magnetic-field strength, and detector system parameters.

Far Infrared Mercury-Cadmium Telluride Photoconductive Detectors

1. Introduction

This program was motivated by the observation of Dornhaus et al.[1] that at low temperatures ($\approx$ 5 K), the excess-electron lifetime in $Hg_{1-x}Cd_xTe$ alloys with $0.165 < x < 0.216$ is increased by more than an order of magnitude when a magnetic field ($<$ 1.0 T) is applied. This effect is expected to produce a corresponding improvement in the responsivity and detectivity of long-wavelength photoconductors because of the direct dependence of these quantities on the excess-electron lifetime.

Because present far-infrared detectors must be cooled below 77 K to optimize their performance and a large enhancement of the electron lifetime can be achieved with small permanent magnets, the operational requirements of a magnetic-field-enhanced detector system are not expected to differ significantly from more conventional extrinsic photoconductive detectors.

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2. Research Objectives

The general objective of this research program was to conduct a systematic experimental and theoretical investigation of the effect of magnetic-field strengths on increasing the lifetime of photo-excited excess-electrons in $Hg_{1-x}Cd_xTe$ alloys with $x < 0.24$ at low temperatures. Because of the difficulty in preparing pure $Hg_{1-x}Cd_xTe$ alloys for long-wavelength applications, there have been few investigations of the behavior of the excess-electron lifetime in narrow-band-gap $Hg_{1-x}Cd_xTe$ alloys with $0.16 < x < 0.24$ and no measurements below 77 K. This information was required to unambiguously identify the physical mechanisms responsible for magnetic-field enhancement of the excess-electron lifetime, and a systematic study of the far-infrared photoconductive lifetime in HgCdTe as a function of alloy composition, charge-carrier concentration, and temperature was therefore undertaken prior to performing the magnetic field studies.

The specific objectives for the work to be accomplished during this study were:

- Measure the photoconductive response and lifetime as functions of infrared wavelength and magnetic-field strength for homogeneous, characterized, HgCdTe alloys.
- Analyze the data to determine the dependence of photoconductive lifetime on alloy composition, charge-carrier concentration, temperature, magnetic-field strength, and Voigt and Faraday configurations.
- Formulate the quantum theory of the magnetic-field dependence of the Auger-recombination rate of photo-excited charge-carriers for HgCdTe alloys.
- Attempt to determine the physical mechanisms that produce lifetime enhancement by magnetic fields.
- Calculate the responsivity, noise-equivalent power, and detectivity as functions of magnetic-field strength for variously configured HgCdTe detectors.

3. Results

Because of the sensitivity of photoconductive properties on alloy composition, temperature, impurities, and defects, great care was taken to perform precise sample characterizations. The material for this contract was purchased from Cominco American, and over 30 single-crystalline wafers of n-type $Hg_{1-x}Cd_xTe$ with $0.14 < x < 0.25$ were procured and screened for compositional homogeneity. From this analysis, samples that met the homogeneity requirement for this work ($\Delta x < 0.001$) were obtained and fabricated into six-contact photo-Hall bar elements. Considerable difficulty was experienced in obtaining suitable long-wavelength $Hg_{1-x}Cd_xTe$ alloys with $0.17 < x < 0.19$. The samples were between 80-150 μm thick in order to minimize recombination at the back surface. The front surface was passivated by the growth of a native-oxide layer. However, spectral-response measurements showed that the native-oxide film strongly absorbs the long-wavelength incident radiation in alloys with $x < 0.195$; therefore these samples could not be used for spectral-response measurements. Further work is required to obtain coatings that passivate $Hg_{1-x}Cd_xTe$ surfaces and are transparent to wavelengths > 12 μm.

Complete characterizations of the Hall coefficient, electrical resistivity, photoconductive spectral response, and excess-electron lifetime were performed from 5 to 300 K for samples with x-values of 0.178, 0.182, 0.189, 0.193, 0.203, 0.205, 0.222, and 0.242. For these samples the temperature dependences of the electron concentration and mobility were theoretically analyzed to give donor and acceptor state concentrations, as demonstrated in Figure 1 for the sample with $x = 0.187$. As shown in the figure, the presence of shallow donor states was observed in the temperature dependence of the electron concentration below 80 K. Donor states were also identified in the near-band-gap photoconductivity spectra of some samples above 60 K. For all samples, the temperature dependences of the energy gaps obtained from the photoconductivity spectra were in close agreement with the empirical relationship used to analyze the electrical data.[2]

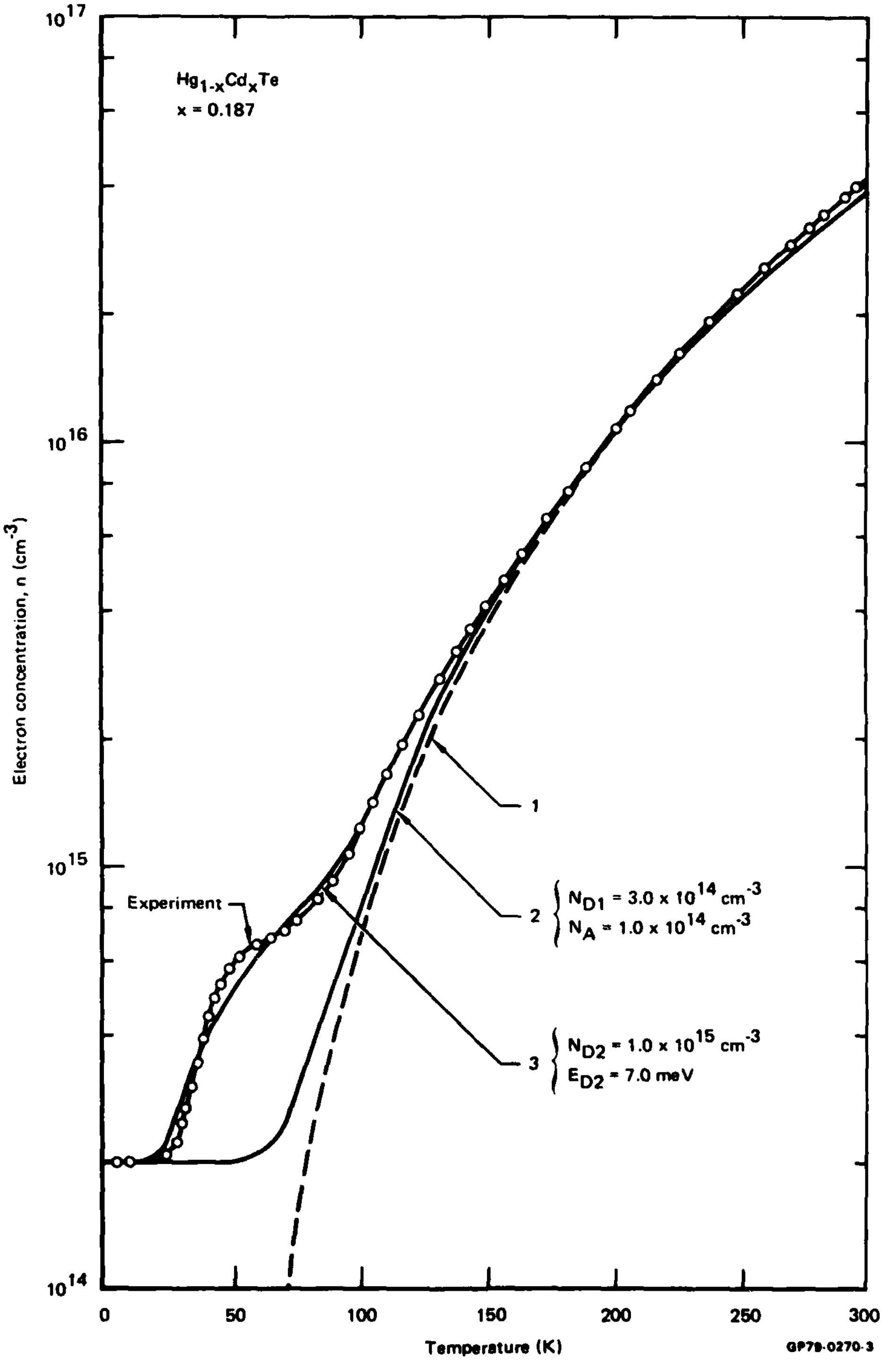

Figure 1. Measured and calculated temperature dependences of the electron concentration for $Hg_{0.813}Cd_{0.187}Te$. Curve 1 shows the calculated temperature dependence of the intrinsic carrier concentration, and curves 2 and 3 show the calculated temperature dependence of the electron concentration for a one- and two-donor level model, respectively.

A comprehensive theoretical model was formulated to analyze the temperature dependence of the excess-electron lifetime. The model includes the conventional recombination mechanisms: band-to-band Auger recombination,[3] band-to-band radiative recombination,[4] Shockley-Read recombination,[5] minority-carrier trapping,[6] and the effects of the surface recombination velocity and the incident background photon flux on the measured electron lifetime. For all samples with peak lifetime values > 1 μs, a characteristic dependence of the excess-electron lifetime on temperature was observed. As shown in Figure 2 for the sample with x = 0.203, the electron lifetime increases with decreasing temperature and has values of 0.1 μs at 210 K and 2.0 μs at 100 K. On further cooling below 100 K, the lifetime decreases and at 50 K has a

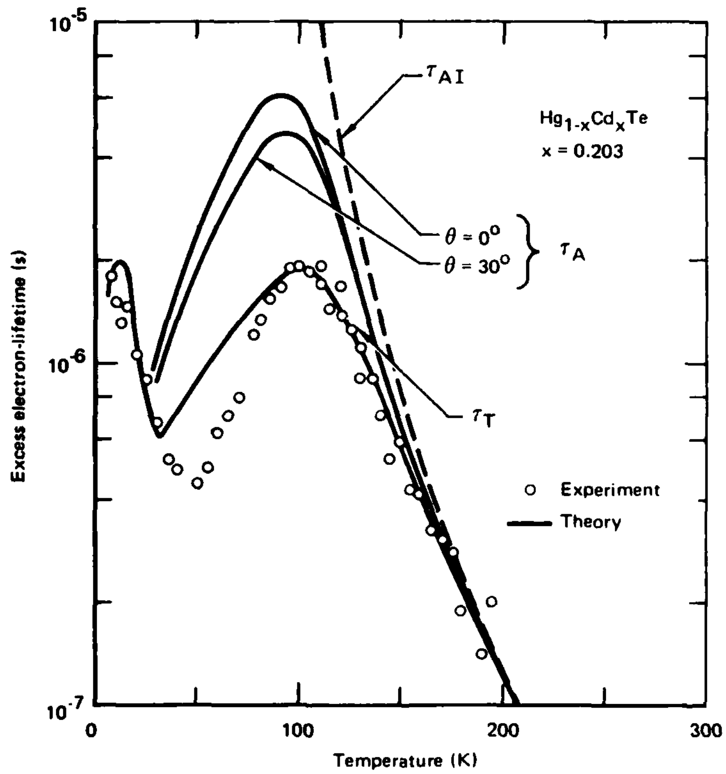

Figure 2. Temperature dependence of the excess-electron lifetime for $Hg_{0.797}Cd_{0.203}Te$. The dashed line shows the temperature dependence of the intrinsic lifetime, τ_{AI}. The Auger lifetime calculated for the sample properties and field-of-views of 0° and 30° is also shown. The solid curve, τ_T, designates the total calculated lifetime including Shockley-Read recombination and minority carrier trapping.

value of 0.4 μs. Below 30 K the lifetime increases rapidly with decreasing temperature and reaches a maximum value of 2 μs at 5 K. Samples with lower x-values showed similar behavior, but the magnitude of the electron lifetime decreases and the temperature dependence shifts to lower temperatures. For higher x-values the reverse behavior is observed. The theoretical analysis of the data shows that the lifetime is limited above 100 K by intrinsic Auger recombination and from 100 to 50 K by Shockley-Read recombination. The behavior of the low-temperature lifetime (< 40 K) is attributed to minority-carrier trapping on acceptor states ~ 0.011 eV above the valence band. The calculations were performed using the electron concentration and donor and acceptor state concentrations obtained from analysis of the electrical data. For a sample with $x = 0.193$ for which the electrical data indicated that the compensation was low, no minority-carrier trapping was observed.

Interband magneto-photoconductivity measurements were performed on samples with $0.17 < x < 0.242$ to determine the magnetic-field dependence of their spectral response and to accurately determine band structure. An example of these results is shown in Figure 3 for a sample with $x = 0.203$ at 5 K. Figure 4 shows a fan chart for the interband transition energies as a function of magnetic-field strength for the same sample. Calculations of predicted transition energies are in good agreement with the experimental data using the band parameters $E_G(0) = 0.06$ eV, $p = 8.6 \times 10^{-8}$ eV cm, and $\Delta = 1.0$ eV, where $E_G(0)$, P, and Δ are, respectively, the energy gap at zero field, the momentum-matrix element connecting the valence and conduction bands, and the spin-orbit splitting.

New phonon-assisted interband transitions were identified in the data when the magnetic-field strength was increased to make the conduction-electron cyclotron resonance frequency greater than the longitudinal-optical phonon frequency. These transitions have been predicted by Weiler et al.,[7] but until this investigation had not been observed experimentally. Measurements of the magnetic-field dependence of the excess-electron lifetime were performed up to 9 T for temperatures of 5-30 K for samples with $0.17 < x < 0.24$. For all samples the electron lifetime increased by one to two orders of

magnitude as the magnetic field was applied. An example of the data obtained is shown in Figures 5 and 6 for the samples with x = 0.193 and 0.178. For these samples the photoconductive spectral response extends to ~ 20 and ~ 35 μm, respectively.

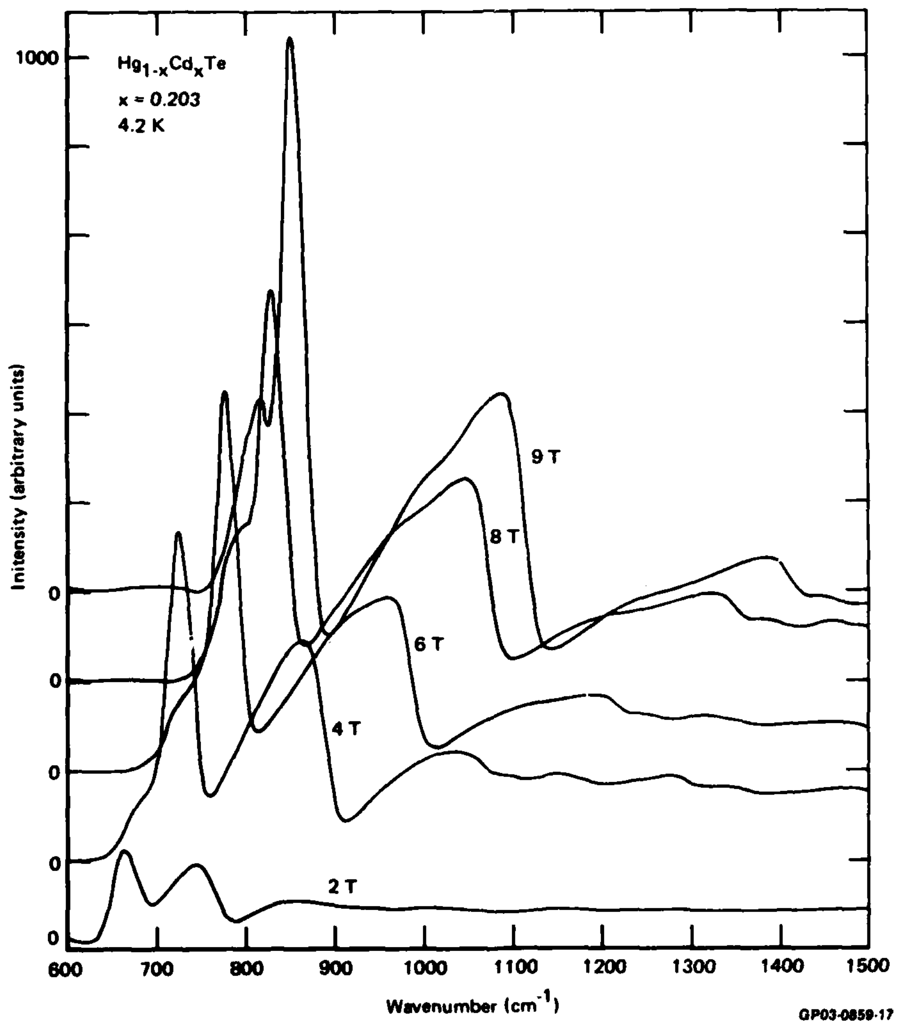

Figure 3. Dependence of the photoconductive spectral response on magnetic-field strength for $Hg_{0.797}Cd_{0.203}Te$.

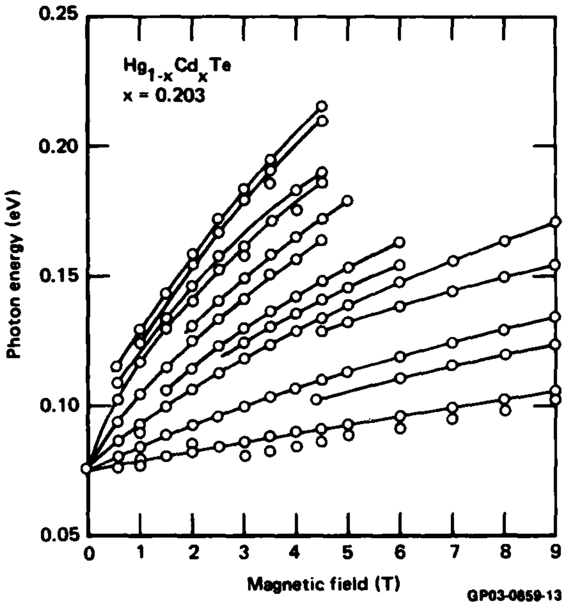

Figure 4. Magnetic-field dependence of interband transition energies for $Hg_{0.797}Cd_{0.203}Te$.

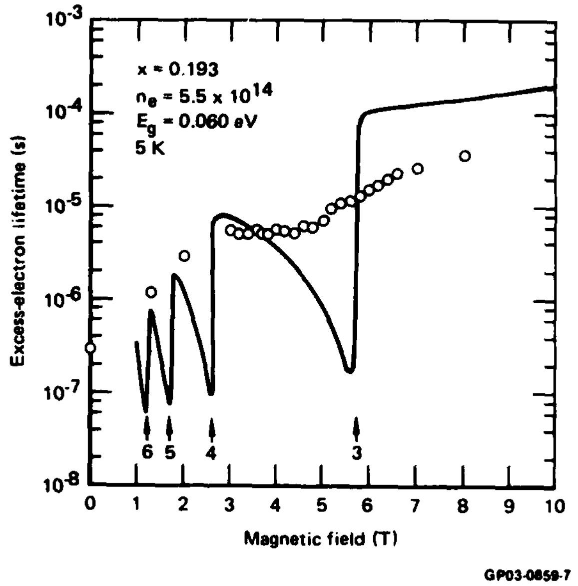

Figure 5. Magnetic-field dependence of the excess-electron lifetime for $Hg_{0.807}Cd_{0.193}Te$ at 5 K. The solid shows the theoretical fit to the data.

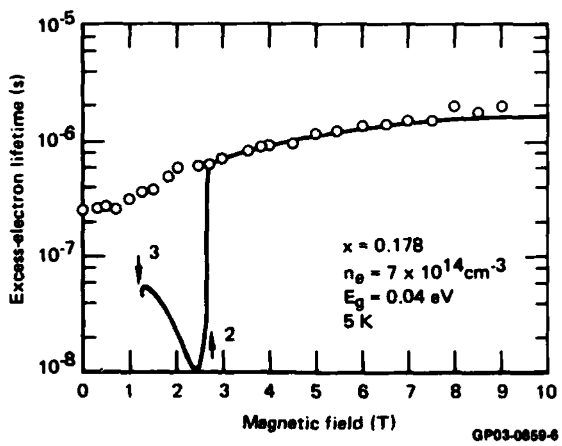

Figure 6. Magnetic-field dependence of excess-electron lifetime for $Hg_{0.822}Cd_{0.178}Te$ at 5 K. The solid curve shows the good theoretical fit obtained to the data for field strengths greater than 3 T.

The theoretical curves shown in Figures 5 and 6 are the results of the Auger limited lifetime calculation described below.

Good agreement was obtained for samples with $x < 0.22$. For higher x-valued samples, whose photoconductive spectral response occurs at wavelengths less than 10 μm, radiative recombination begins to dominate the lifetime characteristics and reduces the effectiveness of magnetic-field enhancement.

The theory of Auger recombination in a magnetic field was developed for the degenerate limit, including the effects of conduction-band nonparabolicity and energy dependence of the transition matrix elements. The validity of the degenerate approximation was established from an investigation of the electron statistics of small-band-gap $Hg_{1-x}Cd_xTe$ alloys in a magnetic field. At 5 K and at zero magnetic-field strength, all of the samples used in this investigation were highly degenerate. As the magnetic-field strength increases, the Fermi energy decreases. However, the lowest value it attains is only slightly below the edge of the lowest Landau level, and the best overall approximation for the range of magnetic fields is the degenerate one.

The physical mechanisms that produce lifetime enhancement by a magnetic field were determined. At low field strengths, the dominant effect is the freeze-out of electrons into the lowest spin-state, which reduces the recombination rate because the scattering between electrons of like spin is much smaller than that between electrons of opposite spin. At higher magnetic-field strengths, a further decrease in the recombination rate is produced by a complex tradeoff between an increasing transition matrix element and a decreasing density of available final states. Oscillations are predicted in the recombination rate (electron lifetime) whenever the separation between conduction-band Landau levels of like spin equals the fundamental energy gap. Only small oscillations are observed experimentally because of other electron-scattering mechanisms.

Possible practical and theoretical factors that affect the performance of long-wavelength detectors were considered. Calculations

of the absorption coefficient spectrum of $Hg_{1-x}Cd_xTe$ alloys with photoconductive responses between 20-40 μm showed that the absorption coefficient decreases rapidly with decreasing band-gap energy. Thus, to achieve optimum performance in long-wavelength alloy compositions, it may be necessary to operate the detector in an integrating sphere.

Detector models were formulated to predict photoconductor performance as a function of alloy composition, donor concentration, temperature, detector field-of-view, background temperature, and sample geometry. Assuming that the lifetime is dominated by band-to-band Auger recombination and neglecting effects caused by sample degeneracy, it is shown that for detectors with spectral response greater than 15 μm, both the detectivity and spectral response are strongly dependent on the excess-electron concentration produced by the background photon flux. The latter effect is a consequence of the Moss-Burstein effect. An example of these calculations is shown in Figure 7 for a 20 μm detector and demonstrates that the 5 K performance becomes superior to the performance at 77 K only when the field-of-view is restricted below 60^{o}. The dependence of the detectivity on donor concentration is shown to be small, but to practically realize these values, it is necessary to have donor concentrations $< 10^{14}$ cm^{-3} to make the element noise voltage greater than the preamplifier noise, which is typically ~ 1 nV.

The increase in both the electron lifetime and element resistance produced by applying a magnetic field is shown to increase the performance of a detector and at the same time relax the stringent requirements placed on material quality. Finally the application of a magnetic field is also expected to be beneficial in increasing the absorption coefficient and spectral range of long-wavelength detectors. By coalescing the available conduction-band energy states into Landau levels, the application of a magnetic field increases the near-band-gap absorption coefficient and decreases the height of the Fermi level in the conduction band. The magnitudes of these effects require further experimental and theoretical investigation.

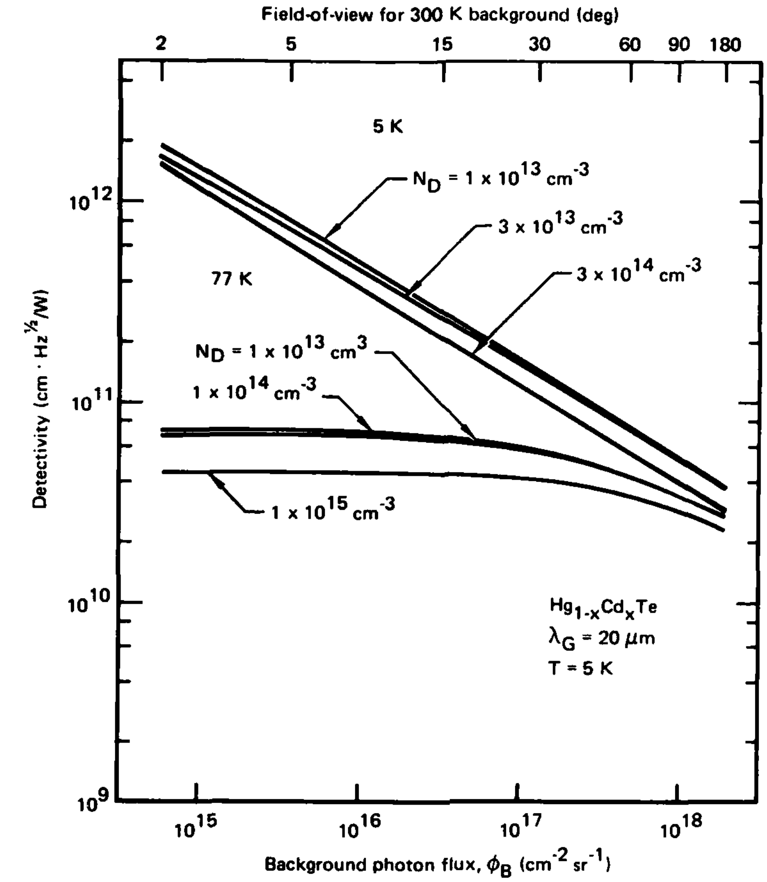

Figure 7. Dependence of detectivity on background photon flux and donor concentration for a 20-μm photoconductive detector operating at 5 and 77 K.

4. Conclusions

All of the specific objectives of this program were accomplished. Measurements of the dependence of the photoconductive spectral response and lifetime were made as functions of alloy composition, electron concentration, temperature, and magnetic-field strength on well-characterized $Hg_{1-x}Cd_xTe$ samples with $0.17 < x < 0.24$. The mechanisms that control the electron lifetime in zero magnetic field were identified. The theory of the magnetic-field dependence of the Auger-recombination rate was formulated in the degenerate limit, and the mechanisms that product lifetime enhancement by magnetic fields were determined.

Computer algorithms were formulated to calculate detector responsivity, noise-equivalent-power, and detectivity as functions of magnetic-field strength, alloy composition, donor concentration, temperature, field-of-view, background temperature, and sample geometry.

5. Publications

Three manuscripts describing the above research activities are being written for publication.

- "Temperature Dependence of Excess-Electron Lifetime in Small-Band-Gap $Hg_{1-x}Cd_xTe$ Alloys", by C. J. Summers and P. Koppel, to be submitted to the Physical Review.
- "Magneto-Photoconductivity in Small-Band-Gap $Hg_{1-x}Cd_xTe$ Alloys", by C. J. Summers and J. G. Broerman, to be submitted to the Physical Review.
- "Performance Limitations and Performance Enhancement of Long-Wavelength (10-40 μm) $Hg_{1-x}Cd_xTe$ Photoconductive Detectors," by C. J. Summers, to be submitted to Infrared Physics.

6. Professional Personnel

The principal investigator for this research was Dr. Christopher J. Summers, Senior Scientist, MDRL. The quantum theory of magnetic-field effects on electron lifetime was formulated by Dr. James G. Broerman, Senior Scientist, MDRL.

Dr. Summers was assisted in electrical and optical screening of HgCdTe alloy specimens by Mr. Paul Koppel.

7. Interactions

The results obtained from this contract were presented at the following conferences and meetings.

- "Electrical and Photoconductive Properties of Small-Band-Gap $Hg_{1-x}Cd_xTe$ Alloys", by C. J. Summers, F. R. Szofran, P. Koppel, and J. G. Broerman, American Physical Society Spring Meeting, Washington, DC, 23-26 April 1979; Bull. Am. Phys. Soc. 24, 586 (1979).
- "Performance Characterizations of Long-Wavelength $Hg_{1-x}Cd_xTe$ Photoconductive Alloys," by C. J. Summers and P. Koppel, Fourth International Conference on Infrared and Near-Millimeter Waves, Miami Beach, FL, 10-15 December 1979.
- "Electron Recombination Mechanisms in $Hg_{1-x}Cd_xTe$ Alloys with $x > 0.24$", by C. J. Summers, P. Koppel, and J. G. Broerman, American Physical Society March Meeting, New York, NY, 26-28 March 1980; Bull. Am. Phys. Soc. 25, 362 (1980).

Discussions and exchanges of information have taken place as a result of C. J. Summers' attendance at the following professional meetings.

- Physics of Compound Semiconductor Interfaces, 30 January - 2 February 1979, Monterey, CA.
- General Meeting of the American Physical Society, 23-26 April 1979, Washington, DC.
- Meeting of the IRIS Specialty Group on Infrared Detectors, 12-13 June 1979, Minneapolis, MN.
- Fourth International Conference on Infrared and Near-Millimeter Waves, 10-15 December 1979, Miami, FL.

- Meeting of the Society for Photographic Instrument Engineers, 4-7 February 1980, Los Angeles, CA.
- March Meeting of the American Physical Society, 24-28 March 1980, New York, NY.

Technical discussions have taken place with 1) T. N. Casselman (Honeywell Corporate Research Laboratories), 2) D. L. Smith (California Institute of Technology), 3) P. M. Raccah (University of Illinois at Chicago Circle), 4) R. E. Longshore (Night Vision and Electro-Optics Laboratory), 5) S. R. Borrello (Texas Instruments, Inc.), and 6) R. F. Brebrick (Marquette University).

8. Patent Disclosures

No patent discoveries were filed or will be filed as a result of this contract. The results obtained are of a scientific nature and serve to define the direction of future $Hg_{1-x}Cd_xTe$ alloy development and to predict optimum performance goals for long-wavelength photoconductive sensors.

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